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SYNOPSIS: The effects of sheet pile installation on an adjacent cohesive soil mass are described herein. Observations indicate that driving sheet pile caused pore pressures to double at some locations. These pore pressures extended further than reported in previous studies concerning driven piles. Initially pore pressures rapidly dropped, but dissipation slowed after this initial adjustment. Inclinometer and extensometer data indicate that the clay was laterally displaced up and away from the sheeting causing the ground surface to heave. The impact of this behavior on subsequent stress changes during excavation is discussed.

INTRODUCTION

The effects of sheet pile installation on an adjacent soil mass are not considered in either the design of braced excavations or predictions of wall movements and surface settlements. As a result, potential deleterious effects of high pore water pressures in cohesive soils on subsequent geotechnical construction are not considered. A literature search revealed scant data on measured ground response to sheet pile installation. However, data have been reported as single piles are driven into the ground.

Ground and bracing system response have been monitored during construction of a 40-ft-deep subway excavation through compressible clays in Chicago. As part of this monitoring program, vertical and horizontal displacements and pore water pressures were measured in adjacent soil as two rows of steel sheet piles were driven. This paper presents a summary of these observations. Because these responses occur prior to excavation and support of a braced cut, they alter the "initial" conditions that are commonly assumed when analyzing braced cut behavior. Possible effects of this prestressing of the soil adjacent to the cut on subsequent response are discussed.

SUBSURFACE CONDITIONS

The subsurface conditions at the test section location consists of 13 ft of rubble fill underlain by a 60-ft-thick sequence of saturated glacial clays, the consistency of which increases with depth from soft to very stiff and hard (Fig. 1). Beneath the clays a 5-ft-thick deposit of sand and gravel overlies limestone bedrock. The water table is located near the bottom of the rubble fill and a downward gradient of flow exists in the lower clays. Finno, et al. (1988) describe these subsurface conditions in more detail and present engineering characteristics of the clays. Note that the Blodgett and Deerfield tills make up the compressible Chicago clays commonly refered to in literature (Peck and Reed, 1954). The subway cut is made entirely within these soft to medium clays, while the sheet piles extend through the very stiff to hard Park Ridge till.

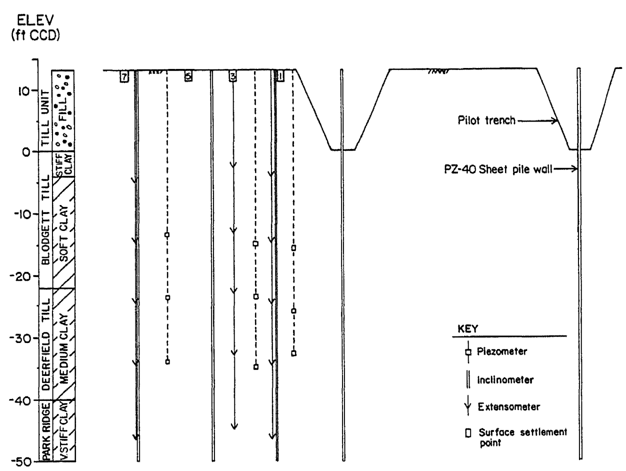

Fig. 1. Elevation at Test Section

CONSTRUCTION PROCEDURES

Two rows of sheet piles were driven to provide temporary support for the excavation (Fig. 1). Prior to driving each row of sheet piles, a 13-ft-deep pilot trench was excavated through the rubble fill because of the presence of large obstructions which would hinder pile driving operations. The construction sequence is summarized in Table 1. The PZ-40 sheet pile wall was installed in two passes. In the first pass along each wall, the contractor drove the sheeting to el.-28 ft Chicago City Datum (CCD); subsequently the contractor drove the sheeting to its design grade of el.-50 ft CCD.

Table 1. Construction Sequence

Day No.	Construction Activity at at Test Section
1	Excavate east pilot trench
3-4	Drive sheeting to el.-28 ft along east wall
7-8	Drive sheeting to el.-50 ft along east wall
15 and 16	Excavate west pilot trench
52 to 54	Drive sheeting to el.-28 ft along west wall
64 and 65	Vibrate and drive sheeting to el.-50 along west wall
101	Begin excavation at section

Notes: Elevations refer to ft Chicago City Datum. Day 1 was December 15, 1986.

INSTRUMENTATION

Ground instrumentation consists of (a) 3 primary instrument clusters placed on a line perpendicular to the sheeting; each cluster contains 3 piezometers at different depths in the clays, one 65-ft-deep slope inclinometer casing, and one 5-point, mechanical extensometer with hydraulic anchors at different depths in the clay; (b) 3 inclinometers and one 5-point extensometer offset from the primary line to provide redundancy in the data, and (c) a surface survey net consisting of 7 reference points (Fig. 2).

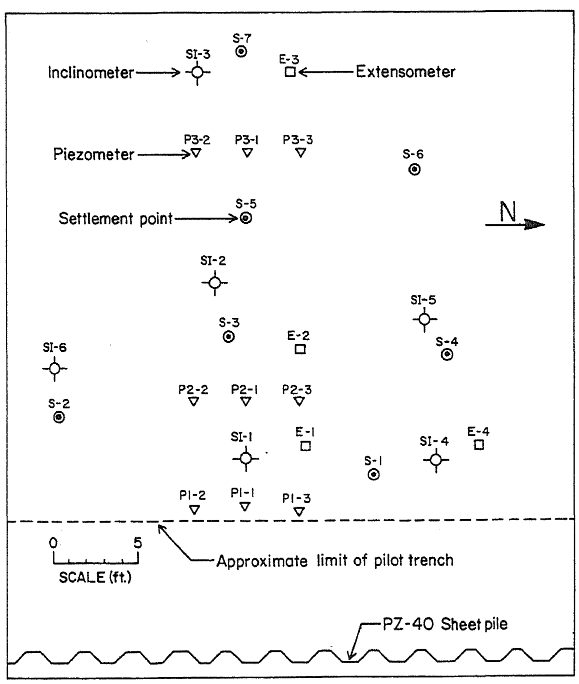

Fig. 2. Instrumentation Plan

Readings were collected during the two months prior to the start of construction at the test section; thus overall accuracy of the installed instrumentation was established. In the period between instrument installation and excavation of the east pilot trench, three sets of SINCO Model 200B slope inclinometer data were obtained. Readings were obtained in orthogonal directions. The angle that the orientation of the inclinometer casing grooves made with a perpendicular line from the sheeting was measured; all data were corrected so that horizontal displacements, both perpendicular and parallel to the sheeting alignment, were obtained. These data indicated that the repeatability of the readings was approximately ± 0.05 in. Manufacturer's specifications indicate that the 200B indicator has a sensitivity of 1 part per thousand. Extensometer data were obtained with a micrometer that read to 0.001 in.; the accuracy of these data were limited to 0.12 in. by survey measurements of the elevation of the top of the reference plate. Manufacturer's specifications indicate that the triple-tube pneumatic piezometers, SINCO Model 514178, are accurate to within 0.30 ± .05 psi. Field tests prior to sheet pile driving indicate that repeatability of the readings was approximately ± 0.05 psi; response of each of these transducers was checked during field installation by comparing observed pressures with those calculated from the height of water in the borehole prior to sealing and backfilling each borehole.

RESULTS OF FIELD OBSERVATIONS

Based on observed response, driving operations along the east wall caused no significant soil deformations or pore pressure changes at the test section location. All significant observations resulted from driving the west wall. The general trends of the observed soil behavior wall are described in terms of displacements that occurred perpendicular to the sheet pile alignment (herein called transverse), displacements that occurred within a horizontal plane, pore pressures, and vertical displacements at both the ground surface and top of the clay strata.

Transverse displacements are shown in Fig. 3. These displacement vectors are plotted for construction days 54 and 66, that correspond to completion of the first and second pass, respectively, along the west side of the test section. The vectors consist of a combination of extensometer data and inclinometer data obtained at elevations of the extensometer points. Maximum incremental displacements were on the order of 0.5 in. Upon initial driving, soil at elevations above the bottom of the penetration displaced laterally and vertically as much as 0.4 in. After final seating of the sheet piles, the soil at lower elevations displaced away from the sheeting, but this time with a more marked horizontal component. A rather large inward component of movement was observed at shallow elevations near the sheeting. While the pattern of movements could be interpreted in terms of a flow around a penetrating object, part of the magnitude of these inward movements near the surface are thought to have been caused by an increase in temperature during this time. The temperature rise would have thawed the frozen rubble fill at the edges of the pilot trench; the fill was observed to be substantially weaker in the thawed state and movements toward the sheeting undoubtedly occurred in the fill as a result.

Note that the magnitude of the outward movements

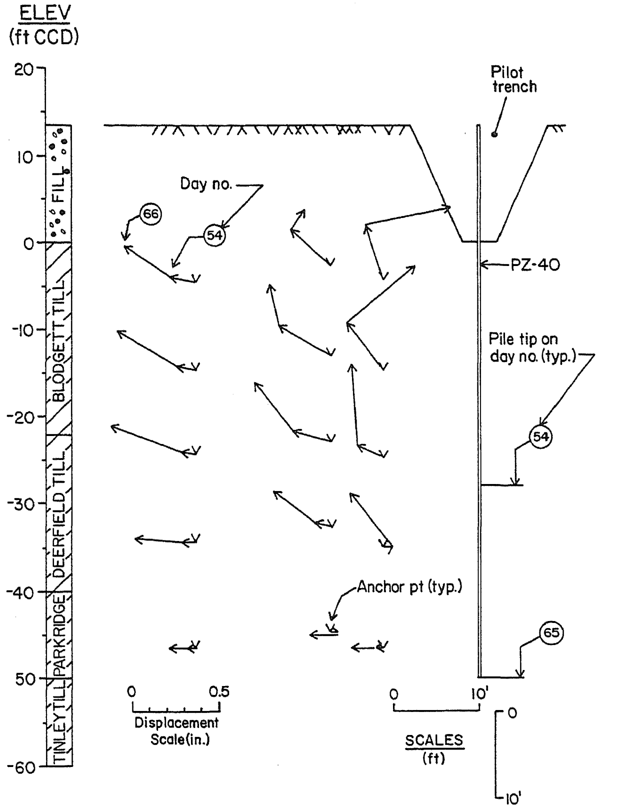

Fig. 3. Transverse Displacements During Driving

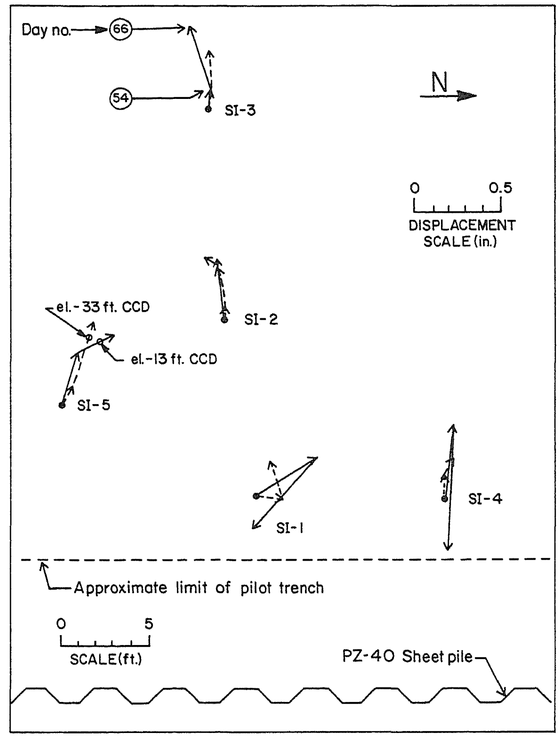

Fig. 4. Horizontal Displacements During Driving

could have been expected. Within the saturated clays, an estimate of the lateral displacement can be made by assuming that a quantity of soil equal to the volume of the section must be displaced. The PZ-40 section displaces an equivalent of 1 in. of soil per foot of section. By assuming that equal amounts displace in each direction, 0.5 in. (13 mm) lateral movement can be expected.

Displacements in the horizontal plane at two elevations within the clay are shown in Fig. 4. Although the trend of the movements is essentially perpendicular to the sheeting, significant northward components of movements were recorded at the locations of inclinometers SI-1 and SI-5. These corresponded to the direction of the pile driving.

Pore pressures during pile driving operations are shown in Fig. 5. The leads to piezometers P1-1 and P1-2 were cut while excavating the west pilot trench. The remaining piezometers show that pore pressures rose rapidly in response to each pass of the sheet pile driving. The largest increases were recorded after the second pass was completed on day 65. After the peak values were observed immediately after driving, the pore pressures dissipated rapidly at first, then decreased at a slower rate.

Sheet pile driving caused time-dependent movements of the ground surface (Fig. 6). Movements at the ground surface were tracked with standard leveling equipment with an estimated accuracy of ± .12 in. To illustrate the relation among

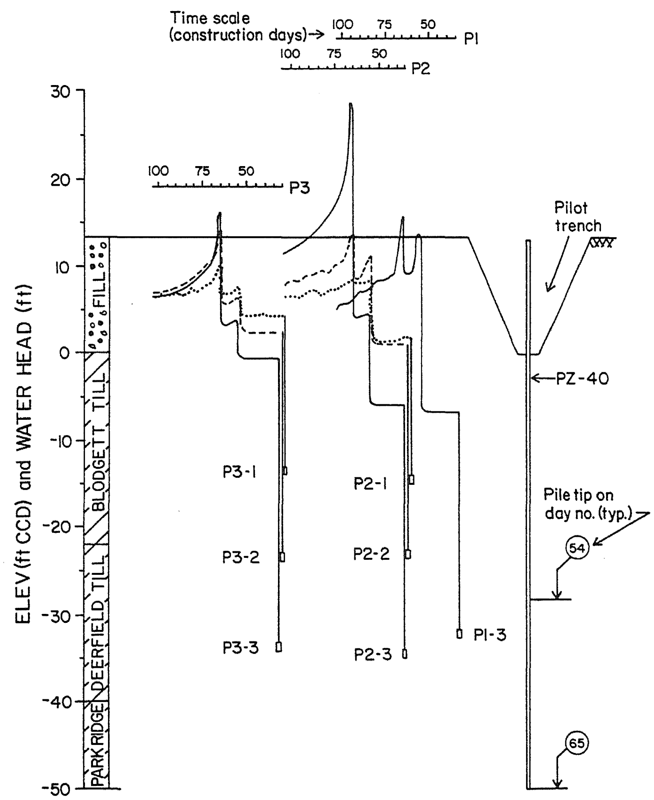

Fig. 5. Pore Pressures During Construction

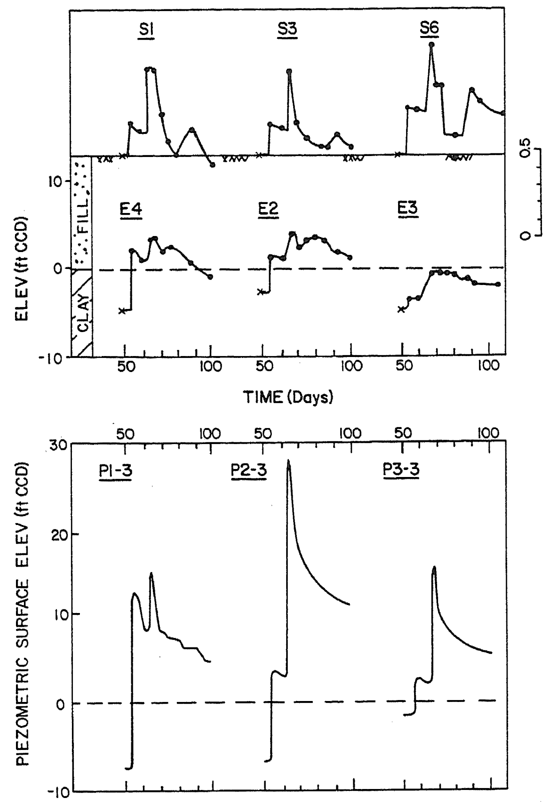

Fig. 6. Vertical Displacements During Construction

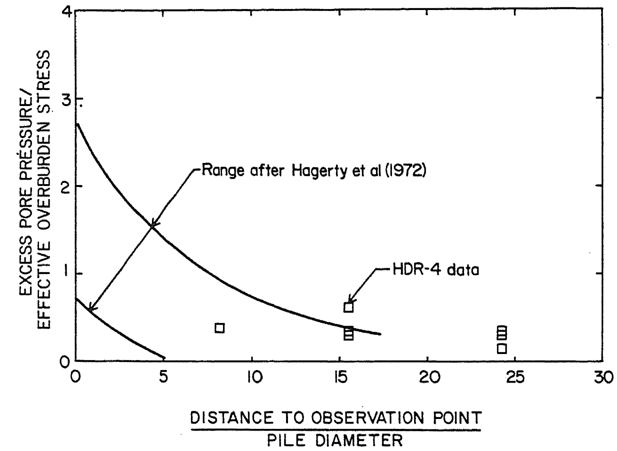

Fig. 7. Comparison Between Pore Pressures For Single Piles and HDR-4 Data

movements, pore pressures and pile driving, vertical displacements at the ground surface and the top of the clay and pore water pressures are plotted versus time for this construction period. The sudden increases in pore pressure correspond to sheet pile driving; the ground surface clearly heaved as a result of installing the sheeting. As pore pressures dissipate, consolidation occurs within the clay, and both the ground surface and top of the clay subsides.

DISCUSSION

The most striking features of the observed response were the pore pressures. Pore pressures during pile driving have been reported by several investigators (e.g., Lambe and Horn, 1965; Orrje and Broms, 1967; Hagerty and Garlinger, 1972; and Flaate, 1972). Their effects on subsequent pile response is well-documented. However, very limited data (i.e., Karlsrud, 1986) are available concerning pore pressures associated with sheetpile driving and their effects on subsequent excavation behavior.

Figure 7 shows the maximum ratios of excess pore pressure/effective overburden pressure plotted versus normalized distance from the sheet pile. Also shown is a band that reflects normalized excess pore pressures caused by driving single piles as reported by Hagerty and Garlinger (1972). The band reflects data from six reported case studies. Note that an equivalent diameter of 1.34 ft, equal to the depth of the PZ-40 section, was used to compute normalized distance. The data indicate that the extent of excess pore pressures can be larger when driving sheet piles than when installing piles. The pore pressures adjacent to the sheet piles could not be measured because of the presence of the pilot trench; however, the magnitudes are expected to follow the same trends as piles. The wider zone of influence for the sheet piles can perhaps be attributed to the differences caused by plane strain conditions associated with sheet piles and axisymmetric conditions associated with piles.

It should be emphasized that these pore pressures are associated with sheet pile driving and are not significantly affected by construction equipment loadings. This is clearly shown in Fig. 6. The transient stress increases caused by the cranes would not significantly stress the soil below the bottom of the rubble fill. In addition, the pore pressures generally were largest adjacent to the sheeting and decreased with distance from sheeting.

The effects of the sheet pile driving on subsequent response during construction can be evaluated by examining the postulated stress path for two soil elements adjacent the wall at the locations of piezometers P2-2 and P2-3 (Fig. 8). Refer to Fig. 5 for locations of P2-2 and P2-3. The stress paths were plotted assuming that sheet pile driving increases the total horizontal stress, while maintaining the vertical stress constant. Total stress changes were computed using an A parameter of 1.0 and the measured pore pressure values. This A value is based on preliminary results of K_0-consolidated, triaxial extension tests.

Stress conditions at 5 different times during construction are presented. After completion of the second pass on day 65, note that the effect of the operation is to preload the soil adjacent to the excavation. Shear stresses are reduced, and normal stresses subsequently increase as consol-idation occurs. These changes create a benefi-cial effect that ameliorates the effects of sub-sequent lateral stress reduction as excavation occurs. In this case, stresses are built into the system to counteract subsequent detrimental stress changes.

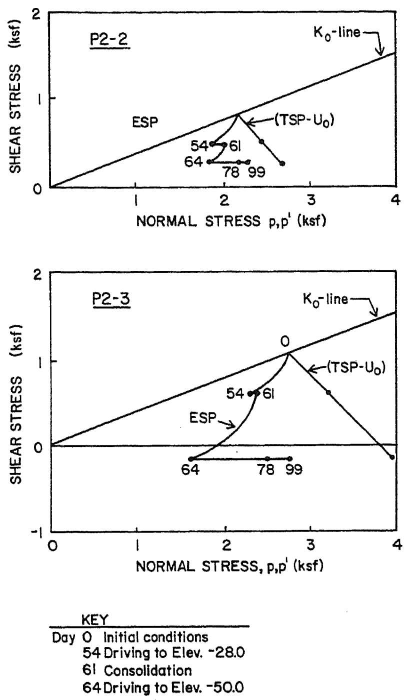

Fig. 8. Estimated Stress Paths During Construction

On the other hand, for soil located between the sheet pile walls below the excavated grade, these stress changes may create a detrimental effect. In this case, as excavation proceeds, vertical stress is reduced to failure. The amount of additional shear stress that can be sustained by the soil is less than that which would exist if pile driving had no effect. This would both reduce the available passive resistance that could be developed by an embedded sheet pile and decrease the amount of movement necessary to generate the full passive resistance.

It should be noted that these paths are based on rather simplified assumptions. A better approximation of the stress paths on both the active and passive sides of the sheeting would be developed on the basis of finite element simulations of the entire construction sequence. These studies will be undertaken in the near future.

CONCLUSIONS

Based on the observed performance data presented in this paper, the following conclusions can be drawn:

1. Driving sheet piles through saturated clay for temporary support of a braced excavation can lead to the development of soil movements away from the sheet piles on the same order of magnitude as the amount of soil displaced by the sheeting. These movements and the associated excess pore pressures are not generally considered in the analysis or design of such works.

2. The excess pore pressures generated by the sheet pile driving operation appear to be on the same order of magnitude as those associated with pile driving, but their lateral extent appears to be wider. This phenomenon may be caused by the difference between the plane strain conditions representative of a sheetpile wall and the axisymmetric conditions representative of piles.

3. The somewhat unexpected response of the soil to the sheet pile installation emphasizes the fact that the profession still can learn much from field observations derived from complete instrumentation schemes.

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